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HORIZON SENSING FOR ATTITUDE DETERMINATION

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Greenbelt, Maryland

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SUMMARY

This report discusses the horizon scanners used in determining the angles between the direction to the center of a body in space and the axes of a spacecraft. Several satellites have used various types of horizon sensors for attitude determination. For example, Tiros satellites and Explorer XVII (1963 9A) used passive scan; Mercury capsules have used conical scan. It is planned that the Orbiting Geophysical Observatory, Nimbus, Gemini, and Apollo programs will include horizon scanners. A scanner accuracy within 1-2 degrees has been obtained for earth scanners. These errors were caused by the radiation pattern of the earth. Data on that pattern for various wave bands are included.

author

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INTRODUCTION

For attitude determination it is often necessary to determine the angles between the direction to the center of a body and the axes of a vehicle. The direction to the center of the other body may be found by calculating the direction perpendicular to the plane of its horizon. In order to determine this plane from a space vehicle, the angles between the direction of the discontinuity between space and the body of interest and the axes of the vehicle are determined at several points on the horizon.

PHYSICAL PHENOMENA WHICH MAY BE USED TO DEFINE THE HORIZON

Several physical phenomena make possible a variety of methods of sensing the discontinuity between space and the body of interest–in other words, the horizon.

Infrared Radiation from the Earth

If the earth is the body of interest, one physical phenomenon which differentiates it from space is the infrared radiation it emits. The earth's horizon may be defined as the sharp gradient of infrared radiation which exists at the limb, or border, between it and outer space.

Since the earth has a fairly uniform temperature this gradient may be used for space navigation under a wide variety of circumstances, whether or not the limb is illuminated by the sun. In other words, it may be used under both day and night conditions. Figure 1 shows the output from an infrared sensor which was mounted in Tiros III (1961 ρ1). As the satellite rotated, the field of view of the sensor scanned the sky, the earth, then the sky again. As the sensor's field of view passed over the horizon, it detected the sharp change in the level of infrared radiation which is represented by the sharp rise in the signal. Passing over the opposite horizon of the earth, it detected the sharp decrease in the level of infrared radiation. It should be emphasized that this

*This report was presented at the Goddard Memorial Symposium of the American Astronautical Society, Washington, D. C., March 16 and 17, 1962.

figure represents fairly ideal conditions. The sharp gradient of infrared radiation which exists at the boundary between the earth and space is the physical phenomenon most commonly used at present for sensing the horizon in space navigation.

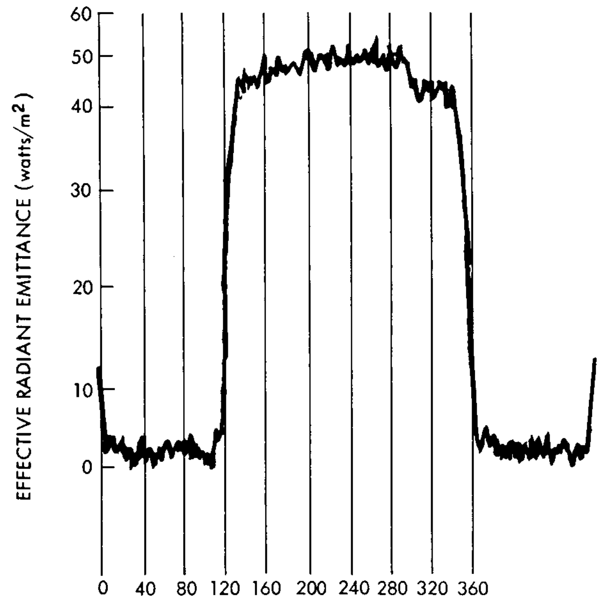

Figure 1—Scan from Tiros radiometer for the spectral range from 8-12μ.

Albedo from the Earth

The ratio between the light received and the light reflected by a body in space such as the earth, sometimes referred to as the albedo, also has been used for horizon determination. However, it is limited in application. At night, when the earth is eclipsing the sun with respect to a space vehicle, no reflected sunlight appears. At other times the earth appears to have phases like those of the moon, complicating the calculation of the horizon plane by means of the albedo. Figure 2, a photograph taken during one of the Mercury suborbital flights, illustrates the phenomenon of albedo. The horizon is easily seen as the gradient between the apparent surface of the earth, which reflects sunlight, and black space beyond, which does not. (The Georgia-Florida coast line is visible in the picture.)

Air Glow Around the Earth

The upper portion of the earth's atmosphere radiates because of excitation by the sun. This phenomenon, known as air glow, could be used to define the horizon. It occurs in both the day and night.

The total visible intensity of air glow is approximately equal to the total amount of starlight seen on a clear, moonless night. Air glow is rarely observed on the surface of the earth because it is evenly distributed throughout the sky. Much of the illumination by air glow is in a few spectral lines. For the sodium line at 5893A, one of the more intense and better known lines, the intensity (relative magnitude) in the summer is 2000 during the day and 230 at night. In winter it is 15,000 during the day and 200 at night. Its intensity during the day is about 75 times the nighttime intensity. Auroral intensity is 1000. This air glow radiation comes from a rather narrow band in the atmosphere occurring approximately 90 km above the surface in a layer about 10 km thick. Some scientists think that if the earth were viewed from a distance, with a sensor which is sensitive to only one particular band of air glow, a doughnut of radiation would be seen circling a dark earth and the rest of space would be dark, except for point sources. The earth's horizon then could be determined by measuring the physical position of the air glow band. Very few measurements have been made of the air glow phenomenon.

Some of the most recent data indicate that air glow intensity varies from point to point over the earth's surface. Its altitude appears to vary with time; altitude measurements have been taken only at White Sands, New Mexico. The picture taken during the suborbital Mercury flight (Figure 2) shows no evidence of the air glow phenomenon. The intensity of air glow in the ultraviolet is only about one ten-billionth of the thermal energy radiated by the earth. This illustrates one of the main limitations on the usefulness of air glow for space navigation purposes.

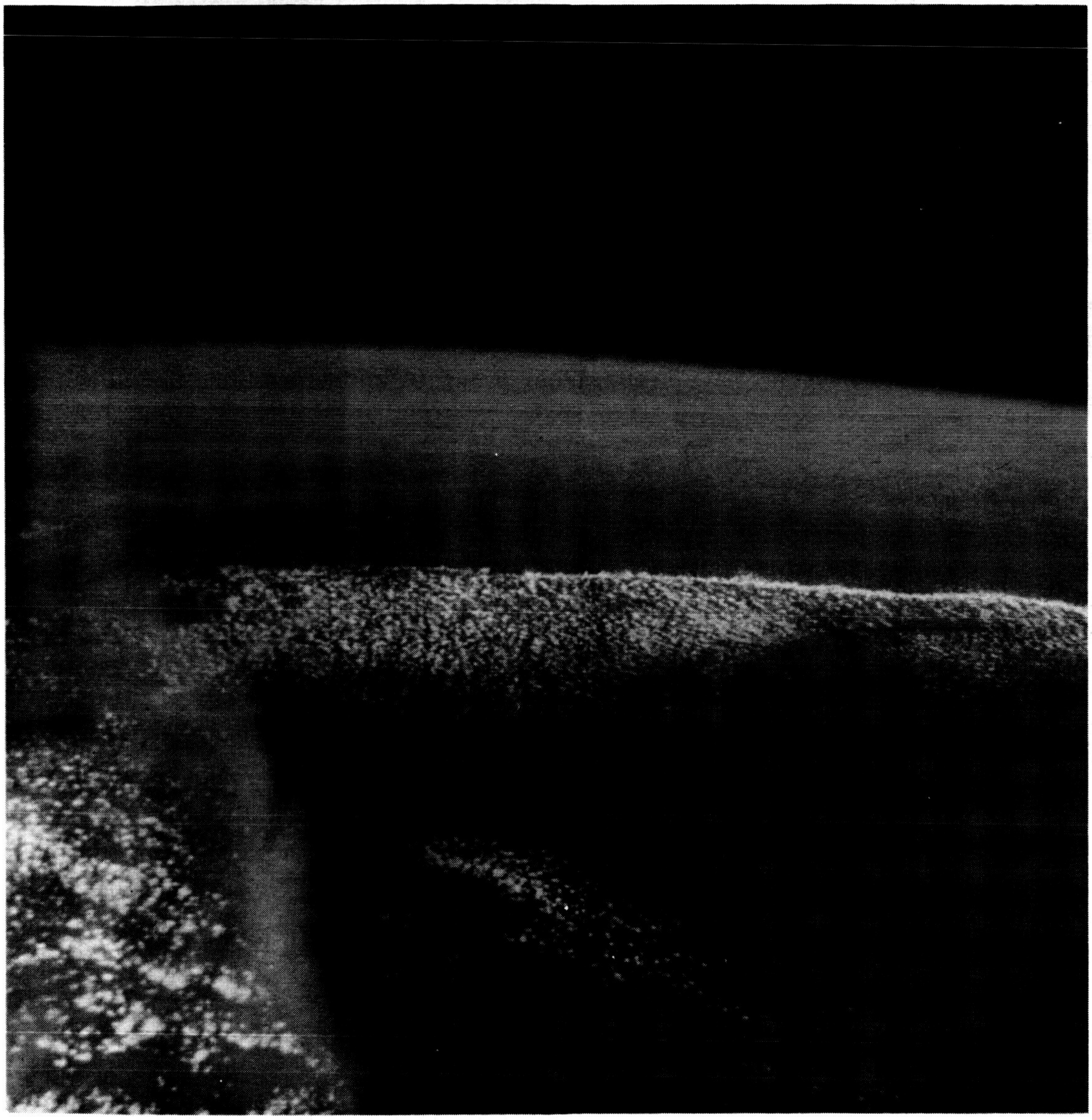

Figure 2–Photograph taken from a Mercury capsule on a suborbital flight.

Other Bodies

The horizons of bodies other than the earth may be defined by use of the general phenomena already discussed:

1. Emitted thermal radiation;
2. Reflected radiation (albedo);
3. Air glow.

The horizons of the nearby planets, Venus and Mars, and perhaps artificial satellites, may be determined by sensing the gradient between the infrared radiation which they emit and that of space.

The visible radiation emitted by the photosphere of the sun may be used to determine its horizon. The horizons of the moon, the near planets, and perhaps artificial satellites may be determined by the gradient of reflected sunlight at certain times.

SCANNING SCHEMES

Any instrument for attitude determination needs, in addition to an intensity sensor, a means for determining the direction of the incident radiation. This means will be called a scanning scheme. Five scanning schemes have been used or proposed for determining the direction of the local vertical.

Passive Scan

The passive scan can be used only on rotating spacecraft. A sensor with a small field of view is mounted in the vehicle, its field of view perpendicular to the spin axis of the vehicle. As the vehicle rotates, the field of view of the sensor is swept through space.

The data in Figure 1 were taken with a scanning scheme similar to this. The times at which the field of view of the scanner passes the two horizons can be determined with the use of these data. From these time parameters the attitude of the vehicle at any instant can be determined. This technique was employed with infrared sensors on several Tiros weather satellites, and was used on Explorer XVII (1963 9A). It has also been employed on daytime rocket shots using sensors which detected the earth's albedo.

Conical Scan

A second type of scanning method is the conical scan. Figure 3 shows the Mercury space capsule with cones representing the fields of view which its horizon scanner sensors sweep out in space. The Mercury capsule has two scanners which are used to determine pitch and roll errors. Each scanner, again, has a small field of view, but the rotation of the field of view is done by the scanner itself. It scans a cone out of the space. This cone intersects the earth, and the output of

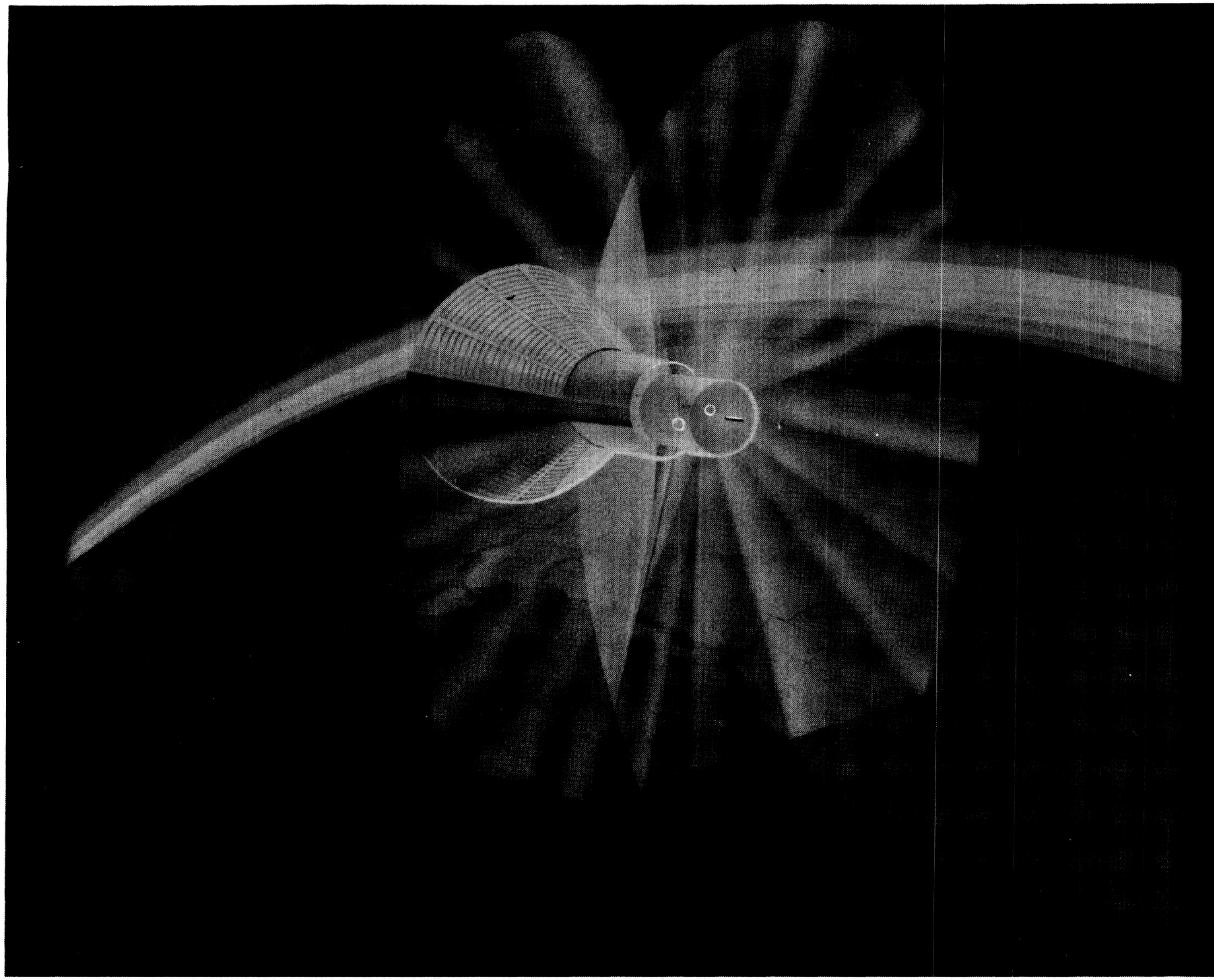

Figure 3—Conical scanning pattern of the horizon scanners on the Mercury capsule.

the sensor is used to determine the location of the gradient of infrared radiation between space and the earth. The local vertical can then be computed. It is presently planned that this type of scan will be used in Nimbus, the advanced weather satellite. The scan pattern is inefficient from an information theory point of view. The information on the direction of the horizon is only a very small part of the information which enters the sensor.

Linear Scan

Figure 4 shows the Orbiting Geophysical Observatory and the linear scan pattern that the fields of view of its horizon scanner sensors sweep out in space. In this case, there are four sensors on the vehicle and they each have small fields of view. These fields of view are rotated in a plane from space until they intersect the edge of the earth. Thereafter, they oscillate at the edge of the earth. Once they have locked on the edge of the earth, the angle between the direction of the fields of view and the satellite can be determined. From this information the direction of the local vertical can be calculated. This type of scanning is better from an information theory point of view than the conical type scan because the sensor field of view spends a longer time at the edge of the earth. Only infrared sensors have been used with these two methods of scanning.

Nutating Scan

Nutating scan is similar to linear scan but uses only one sensor. The field of view of the sensor is again small and is initially on space. It sweeps down until it intersects the horizon. Then it oscillates about the horizon. Meanwhile the whole scanning head is rotated about an axis perpendicular to the field of view. Thus the projection of the sensor field of view on the earth is a sinusoidal pattern along the earth's horizon. The direction of the local vertical is then determined by calculations using the position of the field of view of the sensor with respect to the vehicle at each instant.

Illumination Comparison

A fifth type of horizon sensing does not use moving parts. The illumination on the scanner from one side of the earth is compared with that from the other side of the earth. This information is used to determine the local vertical. On a vehicle within 1000 miles of the earth, it is difficult to image the entire earth on the scanner since such an imaging system would require a very wide field of view. A scanner which uses the illumination comparison method of horizon sensing has been proposed which solves this problem. It uses an infrared sensor and a unique imaging system. A scanner which employs this method has been used on the Ranger moon vehicle. It was designed to determine the direction to the earth from distances greater than 80,000 miles using sensors sensitive to the visible light of the earth's albedo.

PROGRAMS WHICH USE HORIZON SCANNING

Programs which have used horizon sensors for attitude determination include spinning satellites and rockets such as Explorer XVII and the Tiros satellites. The Mercury program has used

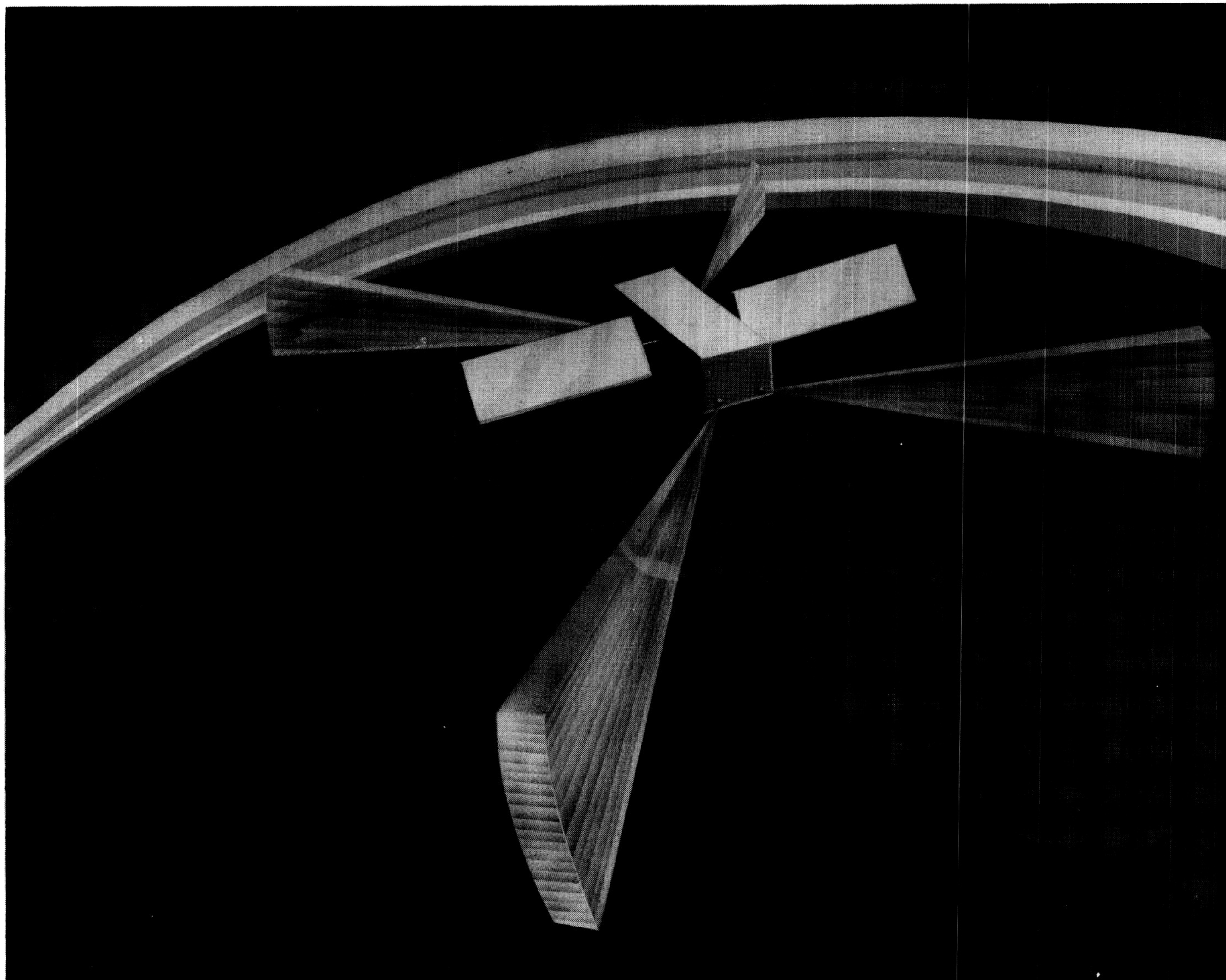

Figure 4—Linear scanning pattern of the horizon scanners on the Orbiting Geophysical Observatory.

horizon scanners; they have also been used to monitor the performance of some NASA rockets and in the Air Force Agena rocket and satellite system. The Jet Propulsion Laboratory has used an earth sensor in its Ranger vehicle.

Future programs planning to use earth horizon scanners are the Orbiting Geophysical Observatory, the Nimbus advanced weather satellite, the Gemini manned vehicle, the Apollo manned vehicle, classified programs for the Air Force, and the Saturn rocket testing program.

Future programs for which earth horizon scanners are under consideration include various communication satellites, rocket probes, and probes to Venus and Mars. Horizon scanners would determine the direction between local vertical of those planets and the vehicle axes. Another future use for horizon scanners may be in the Advanced Orbiting Solar Observatory. This satellite will orbit the earth but observe the sun. An earth horizon scanner could be used to determine the direction to the center of the earth. A sun horizon scanner or limb sensor could be used to determine precisely the direction to the center of the solar disk. A moon horizon scanner may be used on lunar missions such as Apollo.

HORIZON SCANNING ACCURACY

The accuracy of any determination has two basic limitations. One source of inaccuracy is errors developed in the instrument making the determination and the other source is variability in the physical phenomenon utilized for the determination.

Instrument Error

In the case of horizon scanners, sources of instrument error are detector noise, mechanical tolerances, and mounting rigidity. The error caused by a certain amount of detector noise varies, depending on the type of pattern employed. For example, conical scan is more susceptible to detector noise than is linear scan. Detector noise can be made to have as small a contribution to the error of the attitude determination as desired by using large optics, sophisticated scanning methods, and better detectors. Mechanical tolerances in scanners can be made better than a few seconds of arc, if necessary, by good mechanical design. In other words, the error in determining the local vertical due to mechanical tolerances of the scanner can be made smaller than a few seconds of arc. Mounting rigidity can be a problem in some space vehicles. Errors as high as 1 degree can develop if care is not taken. However, alignment of an experiment with a heavenly body can be within 0.1 second of arc if the radiation coming into the experiment is shared with the attitude sensor.

Variability in Physical Phenomena

Earth

The other class of phenomena which cause errors in detecting the local vertical are those due to the heavenly body in question. Errors dependent on the physics of the body generally are a certain magnitude of the apparent diameter of the body and decrease in absolute magnitude as the scanner gets farther away from the body, because of the apparent decrease in angular diameter. The maximum error due to the ellipticity or oblateness of the surface of the earth, in determining the direction of the horizon at one point, is not greater than 0.2 degree. This error could be made zero if the ellipticity of the earth could be taken into account in calculating the attitude. Much larger errors can arise from irregularities in the apparent surface of the earth, such as those that might be caused by high clouds. These may be as large as 0.25 degree at an altitude of 200 naut. mi. but may be mitigated somewhat by the refraction by the atmosphere of the radiation from the tops of the clouds.

Another source of error for some types of scan is cold clouds appearing on the face of the earth. Figure 5 shows recordings from sensors in the horizon scanners in one of the Mercury flights, MA-5 (1961 $\alpha\iota 1$) (see Reference 1). If the output of the radiometer is above the dashed line, the presence of the earth in the field of view is indicated. The horizon is defined by the crossing of this line. In the scan on the left the field of view of the sensor passed over a very cold cloud on the face of the earth. The temperature of the cloud appeared to be about 210°K. At various times during this flight clouds colder than 200°K were observed. This type of cloud emits only about 1/2 the total radiation emitted by an average area of the earth and only 1/4 of the radiation with wavelengths between 8 and 12μ that an average area of the earth radiates. These clouds could cause a great error in the attitude determined by any scanner whose field of view crossed them. The scanner might confuse the cloud with the horizon of the earth. There are scanning methods which are not bothered by the appearance of this type of cloud on the face of the earth. However, they would be bothered by such a cloud appearing at the horizon. In this case the cloud would have a smaller apparent diameter. However its radiation would be augmented by the atmosphere through which it would be viewed.

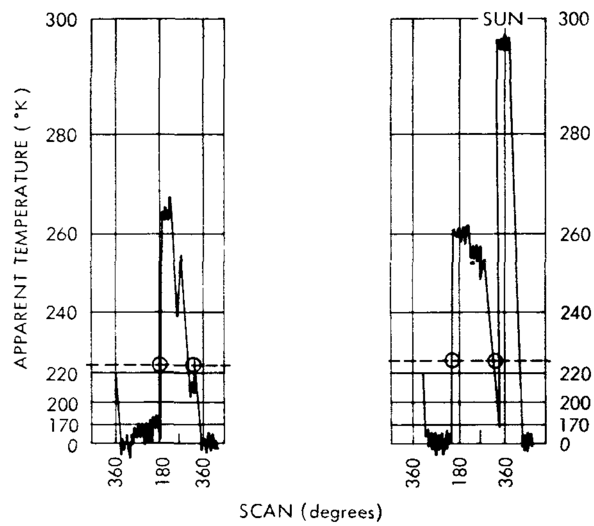

Figure 5–Samples of the horizon sensor signals from the Mercury scanner for the spectral range of 2-15μ.

Dr. Rudolph Hanel has suggested that by using a scanner sensitive only to wavelengths around 15μ, which are strongly absorbed by carbon dioxide, the phenomena of cold clouds could be avoided. Radiations at this wavelength should come from very high in the atmosphere at the top of the carbon dioxide region, above the level of cold clouds (References 2 and 3).

The trace on the right in Figure 5 was taken at a time when the sensor field of view passed near the sun. The signal from the sun appears to the right on the picture. The amplitude of the signal from the sun is clearly stronger than that of the earth, but the scanner could view the onset of the signal from the sun as the horizon of the earth and an attitude determination from this data could be in error by many degrees. It is interesting to note from this data that the apparent diameter of the sun on the trace is about 73 degrees which is much larger, of course, than the apparent diameter of the visible sun in the sky, 0.5 degree.

Several Tiros satellites carried a 5 channel radiometer which senses radiation from the earth in 5 different spectral bands. Figure 6 shows an example of the signals from the radiometer. The first channel is from a radiometer sensitive to radiation of 6.5μ wavelengths. This type of radiation is strongly absorbed by water vapor, so the signal in this channel is from the top of the water vapor in the atmosphere. The signal from this channel shows severe limb darkening. In other words, to the sensor, as it scans over the earth, the wave's shape appears sometimes to be almost triangular rather than square and there is a small gradient of radiation at the horizon. Channel 2 is the signal from the radiometer sensitive to radiation of wavelengths of 8 to 12μ. This is considered to be the water vapor window and the radiation recorded here probably came from near the surface of the earth or from extremely opaque clouds. Figure 1 is actually an enlargement of the signal from this channel. Channels 3 and 5 were sensitive, chiefly, to visible light and were used as a check on the TV camera in the satellite. Channel 4 was sensitive to radiation wavelengths from 8 to 30μ. The signal in this channel is very similar to that of channel 2 which was sensitive to 8 to 12μ radiation. Figure 7 shows an enlarged view of a signal from channel 2. The signals from the Tiros 5 channel radiometer show the cold clouds and sharp gradients on the surface of the earth which also appear in the signals from the Mercury horizon scanner shown earlier (Reference 4).

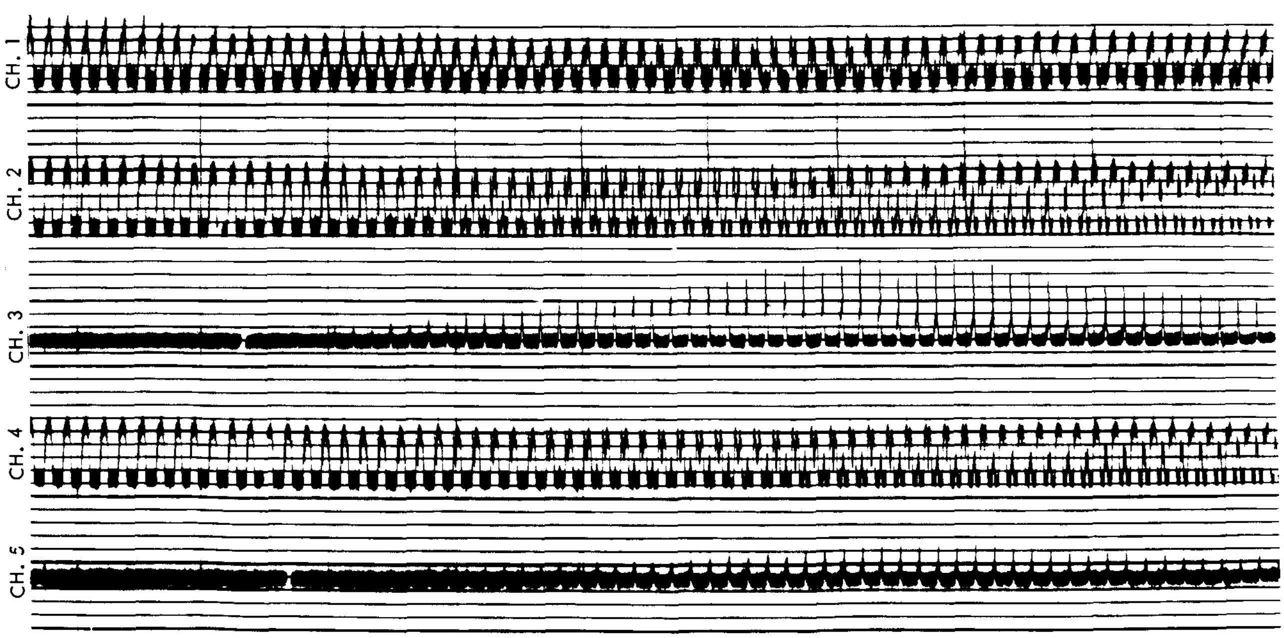

Figure 6—Sample of Tiros radiometer data.

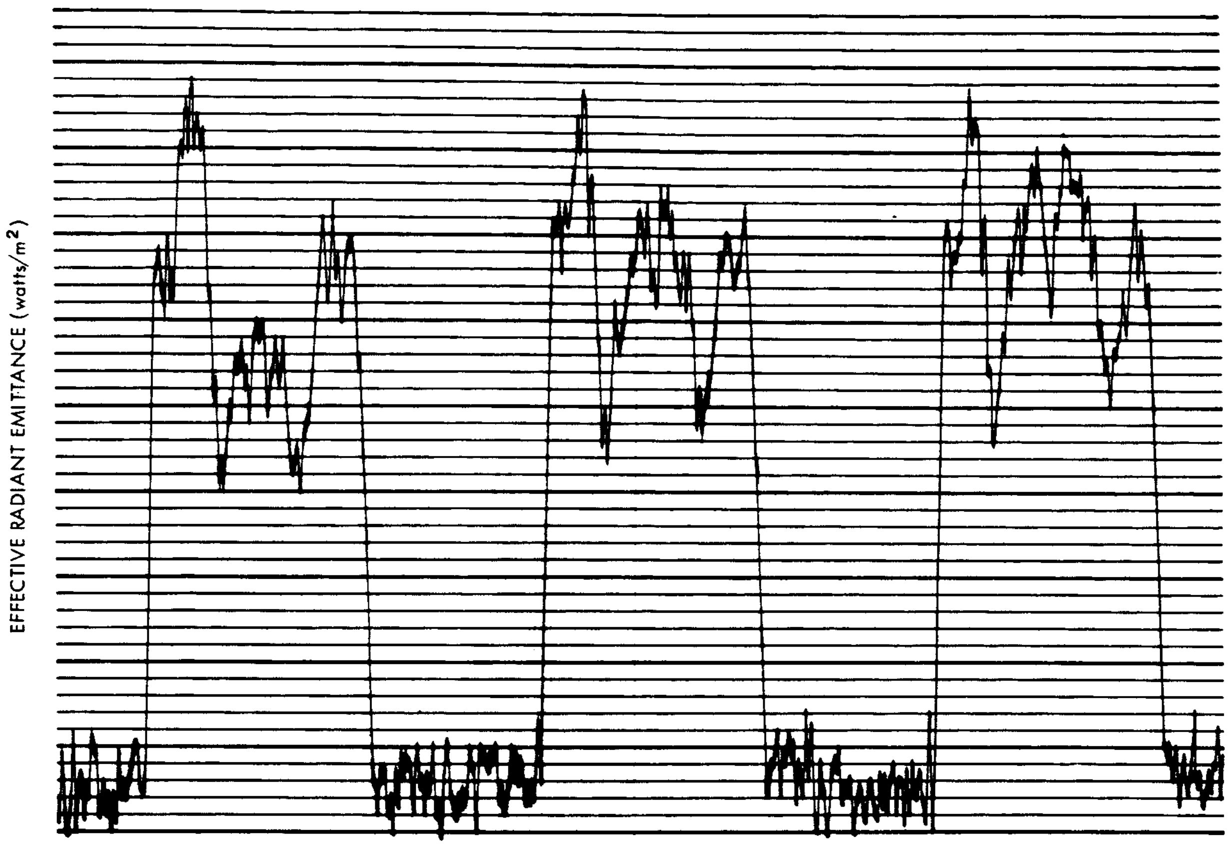

Figure 7—Scans from Tiros radiometer for the spectral range of 8-12μ.

The angular width of the signal from the earth was measured for 34 consecutive scans on channel 2. A level of about 1/5 the maximum signal level was chosen as the "slicing level." The diameter of the earth appeared to vary from scan to scan. The rms variation was 1.8 angular degrees; it can be completely attributed to system noise. The variation in apparent diameter could cause attitude errors of this approximate magnitude.

Other Bodies

Mars would look much like the earth to an infrared horizon scanner. It probably has only a few water clouds but may have high, opaque dust clouds. In fact, one interesting and as yet unexplained fact about Mars is that its ellipticity, or oblateness, as calculated from the orbits of its satellites is 1/2 that measured on photographs of the planet. A reasonable hypothesis which explains this anomaly is that the solid surface has the ellipticity predicted by the motion of the satellites, and the apparent equatorial bulge is caused by dust clouds. Mars' actual ellipticity is somewhat less than the earth's but its *apparent* ellipticity is almost twice the earth's.

This or a similar phenomenon could also occur on the earth, causing errors in horizon scanners. The earth's apparent shape when it is viewed with radiation of certain wavelengths, and the consistency of that shape with time, have not been determined experimentally.

In the past, the attitude of a spacecraft with respect to the sun has been determined by sensors which use the illumination from the total solar disk. However, sunspots can have an area equal to 1/300 of the total disk of the sun. A sensor which compares radiation from the two halves of the solar disk could thus be in error by 5 seconds of arc. For a precise determination of the direction of the sun, a method of limb tracking or horizon sensing of the sun must be used.

Experimentally Determined Accuracy

Tiros satellites have also carried another infrared sensitive horizon scanner called the horizon pipper. The attitude of the satellite was calculated by reducing the horizon pipper data and also from the horizons and other landmarks appearing on the TV pictures from the satellite.

If the best data from the scanner are hand selected and smoothed with a computer, the attitude determined from these data agrees with that determined from the TV pictures to within 1 or 2 degrees. The attitude determined from the TV pictures is considered more accurate.

An accuracy of 1 degree of arc was specified for the horizon scanner on the Mercury capsule. Figure 5, recorded from the Mercury scanner, indicates that the scanner failed to remain within the specified 1 degree error at certain times.

CONCLUSION

In conclusion, horizon scanners for attitude determination, up to now, have been limited by instrument design rather than by errors due to the body which they have scanned. The accuracy of scanners which have been flown has been, at best, 1 or 2 degrees. It appears that an accuracy of 0.2 degree for altitudes below 1000 miles and 0.1 degree for altitudes above 1000 miles will be attainable by techniques now in development.

The use of physical phenomena other than the total infrared radiation from the earth, such as air glow or narrow spectral band infrared radiation, may be necessary to attain better accuracy. More information must be known on these phenomena before horizon scanners can be designed to use them.

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